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After Action Report to the Joint Program Office: Center for the Robotic Assisted Search and Rescue (CRASAR) Related Efforts at the World Trade Center

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ADMINISTRATIVE INFORMATION

This report was prepared for the Office of the Secretary of Defense Joint Robotics Program, Unmanned Ground Vehicles/Systems Joint Program Office (UGV/S JPO) by the Adaptive Systems Branch (Code 2371) of the Advanced Systems Division (Code 237), SSC San Diego, and originally delivered to the UGV/S JPO in October 2001.

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CONTENTS

Tables

1. SUMMARY

We report on the lessons learned from the deployment of the Space and Naval Warfare Systems Center, San Diego (SSC San Diego) urban robot (URBOT) in the search and rescue efforts following the 11 September 2001 terrorist attack upon the World Trade Center (WTC) in New York City. Based upon these lessons learned and upon our earlier experiences with the development and operation of small tactical mobile robots, we then provide specific recommendations for the further development, deployment, and operation of civilian remotely operated search and rescue (ROSAR) robots.

The major deficiencies noted in the current generation of remotely operated vehicles for the urban search and rescue tasks included limited situation awareness, limited mobility, and limited protection from environmental hazards. The unfamiliarity of the first-responders with the robotic technologies also limited their use in the search and rescue operations.

Integrated Product/Process Development Team (IPPDT) procedures now employed within the Department of Defense (DoD) robotics development community could be profitably applied to the search and rescue problem. Federal Emergency Management Agency (FEMA) and local first-responder organizations should be invited to participate with the established DoD robotics programs to improve the definition of requirements and new operational procedures, and facilitate the rapid prototyping and introduction of robotic tools into the inventories of the local first-responder organizations.

2. INTRODUCTION

2.1 PURPOSE AND SCOPE

The purpose of this report is to provide the Program Manager for the Unmanned Ground Vehicles/Systems Joint Program Office (UGV/S JPO) of the Office of the Secretary of Defense Joint Robotics Program with a quick summary of the introduction of small teleoperated robots to disaster-related search and rescue operations following the 11 September 2001 terrorist attack upon the World Trade Center in New York City. This report will also list certain lessons learned from that event and propose recommendations based upon those lessons for future development, deployment, and operation of urban search and rescue robotic tools.

The scope of this report is limited generally to the experiences of the SSC San Diego URBOT team; however, where possible we include additional information that was generously provided by four other technology team leaders who were also involved in the WTC search and rescue efforts.

2.2 ORGANIZATION OF THIS REPORT

Our report is organized around a brief review of the Center for the Robotic Assisted Search and Rescue (CRASAR) efforts at the WTC, followed by a listing of the most salient Lessons Learned. We continue with a discussion of the possible roles for teleoperated and automated robots in different urban search and rescue scenarios, and conclude with recommendations for the definition of requirements, development of enabling technologies and operational doctrine, and the training of first-responder personnel.

2.3 SOURCES OF INFORMATION

We list the names of the contributing technology team leaders in Tables 2 and 3 and in the references section. The information gained primarily from the contributors is referenced with their names in bold type and brackets. All other materials that are not so referenced are the constructions of the authors.

Most of the technology teams that we interviewed were called to the WTC disaster site by John Blitch, the CRASAR director.

The reader may find another source of information on the CRASAR efforts on a University of South Florida web site **[USF]**. This web site, posted by Dr. Robin Murphy, lists the teams participating in the CRASAR efforts at the WTC and some of the results obtained. The site also contains images of some of the robots that were used in the urban search and rescue effort at the WTC site. A useful timeline of the participation of the different teams is also provided.

Many of the team leaders of the technology teams that participated in the WTC disaster search and rescue efforts, and that are mentioned in this report, are in the process of preparing their own detailed After-Action Reports. They may be contacted directly for additional information.

3. ROBOT-RELATED ACTIVITY AT THE WTC

Table 1 lists timelines and robotic assistance efforts.

Table 1. Relative timelines of WTC disaster events and robotic assistance efforts. **[Timeline]**

Date	Time	Event
11 September	**8:48 a.m.**	American Flight 11 crashes into north tower of World Trade Center.
	9:06 a.m.	United Flight 175 crashes into south tower of World Trade Center.
	9:17 a.m.	Federal Aviation Administration shuts down all New York City-area airports.
	9:21 a.m.	All bridges and tunnels into Manhattan closed.
	9:55 a.m.	South tower of World Trade Center collapses.
	10:29 a.m.	North tower of World Trade Center collapses.
	11:00 a.m.	New York mayor orders evacuation of lower Manhattan.
	5:25 p.m.	Empty 47-story Seven World Trade Center collapses.
	5:25+ p.m.	Most Firefighter and other search and rescue personnel are ordered to withdraw from the WTC site.
12 September		All firefighting activity remains suspended.
	3:00 p.m.	First CRASAR personnel arrive at lower Manhattan. **[Frost]**
	3:00+ p.m.	First tasking of CRASAR robots to the WTC site. **[Mangolds]**
13 September		DOE/DOJ Team arrives at the WTC site.
14 September		NYFD personnel begin hand excavation of debris to search for survivors.
		First-responders recover three NYFD personnel who were trapped by the collapse of buildings adjacent to the World Trade Center.
		No survivors from the previous days' incidents discovered.
	12:01 p.m.	Navy's URBOT team first arrived at the disaster relief coordination center.
15 September		No survivors recovered.
16 September		No survivors recovered.
17 September		No survivors recovered.
18 September		SSC San Diego URBOT team returns to San Diego
24 September		Heavy equipment is moved in to contribute to the recovery effort.

3.1 SSC SAN DIEGO CONTRIBUTIONS

The JPO tasked SSC San Diego on 12 September 2001 to transport the available URBOTs to the World Trade Center disaster site in New York City and cooperate with LTC John Blitch, who was coordinating several teams with robots, in an attempt to make the robots available to the first responders who were performing the search and recovery efforts.

The SSC San Diego team, composed of Mike Bruch, Robin Laird, and Bart Everett, arrived at Newburgh, New York, on 13 September around 1800, unpacked and tested the robots. On 14 September at 1201, the team with three URBOTs connected with LTC John Blitch and three other robot teams at the disaster site.

The URBOT was used in one deployment, during which the robot was teleoperated by two-way radio through rubble strewn city streets and into the evacuated Marriott Hotel near the WTC site. Video sent back from the URBOT to the operator control unit (OCU) permitted an assessment of the structural integrity of part of the interior of the hotel.

3.2 CONTRIBUTIONS BY OTHER CRASAR TEAMS

Table 2 lists the details of the four teams that were present at the WTC disaster site at various times between 11 September and 20 September 2001.

Table 2. CRASAR teams working at the WTC site.

Team	Lead/POC	Robots
Foster Miller, Inc.	Arnie Mangolds	SOLEM and TALON
IRobot	Tom Frost	PACKBOT
University of South Florida	Prof. Robin Murphy	Inuktun MicroTrac
SSC San Diego	Bart Everett	URBOT

LTC John Blitch provided coordination for the CRASAR teams. The original objective of the teams was to provide technology assistance to the first-responders as required. The teams discovered, however, that the calls for assistance were few.

Two major factors may have contributed to the minimal calls for assistance. First, the collapse of the two World Trade Center towers probably killed instantly most of the people who were trapped on the floors above the impact sites, and left a dense pile of crushed rubble that killed nearly all others who had remained within the immediate vicinity of the structures. Most of the non-first-responder individuals in the surrounding buildings had taken the opportunity to escape before the collapse. Thus there were few locations in which people could have been trapped and survived. Second, the robot technologies were new to the first-responders, and as a consequence, they had not incorporated any robotic procedures into their operations. In such an emergency, the first-responders appropriately worked as they were trained. The robots were simply not part of their inventory of tools, and thus were not thought of as necessary. The robot technology teams were faced with the difficulties of both learning how to use their own robots in that disaster environment, and in quickly adapting their technologies to the needs and practices of the first-responders. Some success was obtained in meeting these difficulties.

The first deployment of robots occurred around 1500 on Wednesday, 12 September. An Inuktun MicroTrac was lowered into a 9-inch vertical pipe to explore the status of a connected horizontal pipe. **[Mangolds]**

The second mission followed almost immediately upon the first after some search personnel had observed the MicroTrac team in action on the first mission. Those search personnel had discovered a small opening near a damaged building. The MicroTrac was again lowered into the space to assess conditions inside. Later a dog and then a human searched the same space for survivors. None were found. **[Mangolds]**

Inuktun robots are produced by a Canadian company, Inuktun Services Ltd. The Inuktun robots at the WTC site included the MicroTrac and MiniTrac variable geometry tracked vehicles (VGTV). These COTS robots were also operated by the South Florida team led by Robin Murphy in cooperation with the Indiana and Pennsylvania FEMA task forces. These robots went into the pile because they were small enough. They were used to explore for survivors though none were found, and for victims (corpses) and body parts, of which some were found.

The iRobot team participated in essentially one deployment. The Packable Robot (PACKBOT) was driven into a parking garage, coffee shop, and flower shop to assess through remote video the structural integrity of the building interiors. The methods of communication used between the PACKBOT and the operator were both tethered and radio. Both methods permitted an ingress distance of approximately 200 feet, limited at that point by a blocked pathway. Both color video and FLIR were used to determine the navigation path and to assess the building structure. The PACKBOTs provided adequate information to assess the unsafe conditions within the parking garage and shops. **[Frost]**

The USF team used the Inuktun robots and focused primarily on exploration of the pile. The USF team using the Inuktun robots discovered several corpses among the rubble over the course of the week of exploration. A more detailed report on the USF missions will be available from the team leader. **[Murphy]**

These results must be viewed in the context of the greater search and rescue effort that involved humans, dogs, and robots. As of 24 September, the totals of victims and survivors discovered included:

- Number of bodies identified to date: 194
- Number of bodies recovered to date: 261
- Number of missing reported to date: 6,453 **[Totals]**

3.3 CONTRIBUTIONS BY NON-CRASAR TEAMS

Two Department of Energy (DoE) organizations, Savanna River and SANDIA National Labs, in cooperation with the National Institute of Justice, sent personnel to the WTC site to assist in the search and recovery efforts. This team was invited by the New York State Office of Emergency Management, which facilitated contacts with the New York Police and Fire Departments. **[Tillery]**

The DoE/Department of Justice (DoJ) team, shown in Table 3, brought primarily video equipment and provided remote video services for a variety of tasks. For example, during the excavation of the rubble pile by heavy equipment, stationary video cameras permitted monitors to closely inspect the uncovered debris for items of interest prior to their further disruption and removal to the landfill. Another interesting application was the harnessing of a video camera to a search dog. This configuration permitted the search dog's handler to observe, from the dog's perspective, the field of view in the direction of the dog's search. **[Tillery]**

Table 3. Non-CRASAR teams working at the WTC site.

Team	Lead/POC	Technology
DoJ/DoE	Chris Tillery	video equipment

4. LESSONS LEARNED

4.1 ROBOTIC TECHNOLOGIES

The major limitations of current robotic technologies for the types of missions encountered at the WTC site were most obvious in the areas of situation awareness and mobility.

Video is the primary source of information for teleoperated navigation and surveillance. The field of view (FOV) on video cameras is only a fraction of the FOV normally available to a human. The difficulties of navigation via video are similar to the difficulties many people experience when trying to drive an automobile at night in the country. Valuable contextual information that would normally be available to the person through peripheral vision in daylight is denied in the dark of night while attention is focused upon the illuminated FOV of the headlights. An operator can see only what is present in the video, thus important targets, or better navigation options may be missed if they lie outside of the video FOV.

Situation awareness during robot teleoperation has been generally adequate using color video cameras in structured/intact environments and where the attitude or orientation of the robot is known. At the WTC disaster site, this was not always the case.

The inadequate situation awareness at the WTC site can be attributed to the consequences of the unpredictability of the environment. When teleoperating the robot through rubble, the operator could easily lose sight of orienting landmarks, and thus become confused as to the attitude and motion of the robot. The operator could not make up for missing information in the video with his/her own experience and knowledge of the relationships of elements in the environment. This further degraded perspective, making size, distance, and texture estimations difficult.

The difficulties of mobility can be attributed to several factors. The robots that were employed all used track drive. While track drive is generally superior to wheels on uneven and unstable ground, it is inferior to arms and legs. Vehicle size limited access to portals with dimensions less than that of the vehicle. Vehicles without tethers could not safely execute vertical drops. Tethers, however, were a disadvantage when the associated drag decreased maneuverability. The tether did permit vertical deployments by the operator easing the robot via the tether down shafts and swinging it into position. However, this could prove impractical for robots larger than the MicroTrac.

Teleoperation was very slow in the unstructured environments and taxing on the operators. Part of the problem was the inadequate situation awareness. Another part of the problem was the absence of automatic capabilities intrinsic to the robot. Without any assistance from the robots, the operators were required to attend intently to both robot navigation and to the evolving search results from the video.

4.1.1 Energy

Most missions were cut short in duration by obstacles blocking the pathways. **[Mangolds]**

The Inuktin robots received power from 12-volt batteries located with the operator through a deployed tether, which the robot pulled off a spool, also located with the operator. Additional power was thus available simply by replacing the battery at the operator's location.

The robots were invariably electrically powered. Their batteries were adequate for the durations of the missions.

4.1.2 Mobility

The usefulness of the Inuktun MicroTrac in these missions was due to its tether that permitted vertical deployment and recovery, and to its tilt camera that permitted some flexibility in pointing the video camera (pan was accomplished by twisting the tether to spin the robot). Later missions employed the SOLEM robot equipped with tether for similar reasons. **[Mangolds]**

The SOLEM robot had less of a tendency to get hung up on obstacles than the Inuktun MicroTrac, which would "high center." The SOLEM was originally equipped with radio frequency (RF) communications, but this proved useless in tightly enclosed and convoluted spaces. The ideal configuration would have been a small but agile tethered robot with pan and tilt video camera and headlights. The tether needed to be strong enough to support the weight of the robot, but light enough not to affect its mobility. The tether was needed also to provide communications and power. Power was not a critical factor in the present environment because most missions were quite short, interrupted by blocked passages. **[Mangolds]**

The iRobot team discovered that it was very difficult to navigate the PACKBOT through the large jagged metallic rubble that constituted a great part of ground zero. In particular, the twisted piles of I-beams presented a unique challenge. **[Frost]**

iRobot has explored the use of multiple robots by one operator on a single OCU: The operator switches between robots, using one as a remote camera to visually monitor the activity of another robot. **[Frost]**

Two robots got stuck in depressions from which they could not climb out. An URBOT became trapped in a displaced elevator carriage, while a MicroTrac got stuck in a crevice.

The track drives performed adequately, but only within limits. In the displaced elevator carriage, the resistance of the obstacle presented by the difference in elevation between the floor of the elevator and the floor of the shaft entrance was greater than the resistance presented by the URBOT tracks on the smooth and dust-lubricated surface of the elevator floor.

The scale of the navigable obstacles was not easily expanded by the configuration of the tracked vehicles.[1]

4.1.3 Sensors

The video did not provide adequate depth and size information to the operators. **[Murphy]**

Invertibility of the image is needed because the video is used for navigation as well as for surveying. **[Murphy]**

FLIR was not useful in the pile for navigation due to the uniformly hot conditions.

The SOLEM robot had a pan as well as a tilt capability to its camera that facilitated exploration. **[Mangolds]**

[1] Stairs and ladders, which are composed of sequences of navigable obstacles, are used by humans to reduce the scale of the obstacles that are presented by elevated platforms.

The utility of video in search and rescue operations may be improved by the application of robotic technologies. First, the simple addition of pan, tilt, and zoom capabilities to video cameras mounted on hand-held booms may permit greater and more easily interpreted imaging of tight remote spaces. Second, the boom itself may be articulated, given additional degrees of freedom with multiple joints for bending and extensions, to permit the limited projection of the terminal video camera through contorted spaces.

4.2 OPERATIONAL ISSUES

4.2.1 Utility

The Inuktun robots were useful in the pile, but the Inuktun MicroTrac tended to plow its way through as opposed to going over small rubble. (The tether may have contributed to this tendency.) Audio sensors were useful to diagnose mobility problems. **[Murphy]**

The smaller Inuktun robots were better suited to the exploration of narrow spaces, while the PACKBOTs and URBOTs were better configured to survey building interiors where navigation was somewhat easier. **[Frost]**

In general the greatest value perceived was the provision of remote sensing capability. The robots were used to poke around in spaces that were difficult to access by humans. As no survivors were discovered in this process, other possible uses for the robots were not explored.

Small robots such as the Inuktun were the most useful for SAR in rubble. PACBOT and URBOT were tested under the same conditions and were deemed most suited for building structure assessment.

4.2.2 Tempo

The teleoperations of the robots were slow compared to the facility of humans operating in the same environments. Speed of operations was not a critical factor after the hope for the survival of the casualties was surrendered.

4.2.3 Communicability

Communications were expected to be a major problem in the urban environment where RF energy is absorbed and/or reflected. However, the URBOT, using digital RF communications did not encounter such problems for the range and other conditions of its deployment. Nonetheless, more restricted communication environments should still be anticipated in urban search and rescue operations. The tethers used by the Inuktun MicroTracs and iRobot PACBOTs permitted reliable point-to-point communications in lieu of RF links, but operators were careful to avoid breaking or snagging the tethers.

4.2.4 Survivability

Due to the timing of the introduction of the robots to the SAR efforts, their operational survivability at the WTC disaster site under conditions of high temperature, falling debris, and flooding water was not tested.

The lack of waterproofing in the MicroTrac’s payload prevented its use in some missions.

As the greater benefit of robots is their expendability relative to humans, robots should be constructed to survive the conditions of fire, suffocating dust, water, gas, and crushing or piercing shrapnel or fallout that prevent or greatly impede human activity.

The PACKBOT is waterproof to a depth of about 9 feet. Waterproofing is necessary because the firefighting efforts left lots of standing water. The URBOT is also waterproof and can be operated in about 7 inches of water.

4.2.5 Transportability

The mass and weight of the robots constituted a handling cost factor for the remote sensing capabilities that they provided.

The robots were all man-portable and posed no problems with transportability under the prevailing conditions. Size and weight did become an issue, however, when the robots were used to explore tight spaces.

4.2.6 Maneuverability

Robots may often be useful where humans cannot go. Small robots can penetrate spaces too constricted for human transit. One problem with small robots, however, is in their inability to negotiate quickly obstacles of sizes that do not impede humans.

Mandelbrot, through his analysis of Fractals, has shown that the complexity of the physical geometry of nature is similar at all scales. This implies that the navigability of obstacles will remain constant regardless of the size of the agent. Large obstacles will impede large agents as much as medium sized obstacles will impede medium sized agents—that may, nonetheless, pass around or through large obstacles and over small obstacles. Small obstacles impede small agents that may, nonetheless, pass around or through medium sized obstacles and over micro-obstacles, etc. Humans rearrange the natural environment to limit the range of obstacle sizes that we are likely to encounter on a particular trajectory (e.g., roadway). A possible adjustment to the complex geometry of nature is to have available robots of different sizes, and to deploy the appropriate size of robot for the prevailing conditions in the environment and the particular needs of the moment. Large robots may themselves deploy smaller robots under certain circumstances.

4.2.7 Operability

Driving the robots through streets and building interiors generally posed little difficulty for the experienced operators, but operation in rubble was considerably more difficult. As navigation requires advanced path planning, the limited sensor information from the robots was inadequate to evaluate the navigation options in the unpredictable conditions of rubble.

4.2.8 Customer Acceptance/Training

The FEMA teams should receive training in the use of the robots prior to an emergency deployment. **[Frost]**

The early tasking of the robot teams was accomplished on an adhoc basis. First-responder personnel, who were aware of the availability of the robots, would call for them from time to time. When the shifts of search and rescue personnel changed, the utility of the robots could be forgotten.

There was no central dispatcher that coordinated the deployments of the various assets at the disaster site. **[Mangolds]**

Team leaders were impressed that the first-responders were willing to risk their own lives as a manner of course and only consider the robot applications when time permitted.

4.3 IMPLICATIONS

Civilian emergency first-responder personnel have had little opportunity to work with robots in search and rescue operations. As a consequence, first-responder personnel are generally unaware of the potential applications of the robot technologies. This situation may be corrected by providing a rapid prototype robot to a sample of first-responder organizations. Personnel within these organizations could then train with the prototype ROSAR robots, gain first-hand experience, contribute to the refinement of the requirements for a more mature and cost-effective product, and develop the operational procedures for a variety of disaster conditions. The experience gained in training would help prepare the first-responder personnel for the employment of ROSAR robots in response to actual emergencies.

Given that on 24 September 261 bodies had been recovered from the disaster site, at a maximum, those 261 lives may have been preserved after the collapse of the twin World Trade Towers had immediate rescue been possible and had those victims not been killed outright by their injuries. This presents an upper limit upon what we could hope to have accomplished in preserving lives of the casualties at the WTC had it been possible to enter the area immediately after the collapse with robots and recover those victims without risk for additional loss of life and injury to search and rescue personnel.

Other types of disasters, in which the forces of destruction would not be so great and so concentrated, may involve considerably more wounded than immediately killed, and therefore offer greater opportunities for success in early intervention.

It is well established that the sooner emergency care can be provided to disaster casualties, the better are the survival outcomes. Many disasters, both natural and man-caused, have effects that persist beyond the immediate disaster event and pose great risk to first-responder personnel. This risk, along with the difficulties of negotiating the disaster environment, often contributes to delays in responding to the needs of the casualties, resulting in additional fatalities.

The provision of immediate search and rescue capability, when the environment remains dangerous or otherwise inaccessible to emergency response personnel, is the driving requirement for the employment of unmanned search and rescue systems, including robots.

4.4 ROBOTIC MISSION AREAS

We identify three general mission areas for ROSAR robots and discuss requirements associated with those mission areas. The three areas are *search/surveillance*, *delivery*, and *recovery*. Search capabilities are fundamental to all three missions, and are therefore more general.

It is widely believed that robots will be most useful in missions for which it is impractical to send a human. This includes not only mission conditions that are dangerous, dirty, or dull, but also the condition in which there is simply not enough people to perform the necessary tasks. Robots could be incorporated into the interesting and beneficial tasks if that would improve the results desired by their human owners and operators.

4.4.1 Search/Surveillance

There can be several reasons for a search capability. Foremost should be for the location and status of survivors. Secondarily should be the location of expired casualties. The robot may also be used to search for high-valued assets, such as aircraft "black boxes," safes, and treasures. The robot may be employed in a situation assessment of the environment, including building integrity, and environmental hazards such as the presence of gas and other chemicals. To perform a competent search, the robot needs good mobility, good sensing, and good communications. Mapping capability facilitated by GPS or INS can greatly aid the operator.

Any significant event uncovered by the robot should be localized in time and in space. Time is simple to record if the data are communicated from the robot in real-time. Spatial localization of the robot can be difficult, however, as the operator may not be able to keep track of the robot's location from the sensor information that is returned. Other strategies already mentioned such as GPS and INS can be used under certain circumstances, but more sophisticated measures such as cooperative triangulation from the deployment of several robots may be required.

Under some circumstances, maps may exist to facilitate the search and rescue operations. This could be the case in intact buildings. However, most disasters rearrange the conformation of structures and reduce the utility of existing maps. In such cases, new maps must be created and maintained as information becomes available from the survey teams, including from the robots. The integration of INS information in three dimensions can provide a three-dimensional map of the trajectory of the robot. Such maps, especially if combined with information from other robots and survey teams may reconstruct navigable pathways through complex disaster environments.

4.4.2 Delivery

Particularly in search and rescue operations, the potential to deliver potable water and oxygen to disaster victims may make the difference between life and death. The appropriateness of any particular payload could be estimated in advance or determined from the information gained by the first robot on the scene and delivered by a backup robot. Examples of other commodities or services that might be delivered include:

- Chemicals for neutralizing and firefighting, etc.
- Water for firefighting
- Light sources to illuminate work areas
- Communications transducers and relays

Ranges in excess of the line of sight limits of RF are commonly achieved through the use of repeaters. The robots can position themselves to act as repeaters or deploy repeater “bricks” as a payload task.

The URBOTs were prepared to deliver emergency supplies of water, air, and plasma through sterile tubes from medical stations to locations within the rubble where victims may have been trapped. The preparation proved unnecessary as no live victims were found.

4.4.3 Recovery

Robots may also be used to transport victims and other high valued items from the most dangerous areas of the disaster. Such a procedure may be worked similarly to the delivery of critical services: A search robot may be followed by a recovery robot. Differences between delivery and recovery robots may exist in the requirements for manipulators.

5. RECOMMENDATIONS

5.1 REQUIREMENTS PROCESS

In order to develop useful tools for robot-assisted search and rescue operations, the robot development community should work closely with the first-responder community. Between these two communities there are many strangers.

An integrated product/process development team (IPPDT) could be managed by FEMA and composed of users from the first-responder community, developers from the academic, military, and industry laboratories, commercial producers, and FEMA program managers with representatives from other DoD and DoE programs. The IPPDT may be self-funded, as all participants should benefit from the cooperation the team would afford.

FEMA may need to provide resources for procurements, training, and operation to local emergency response agency managers who could have difficulty in convincing local governments of the need to acquire novel robotic technologies.

The DoD program managers and the robotics development community could assist the first-responder community to discover better operational procedures that can take advantage of the new technologies. We outlined three general application areas in the Section on *Robotic Mission Areas* of *Lessons Learned* above.

5.2 SYSTEM SPECIFICATIONS

5.2.1 Cost

As in military applications, cost is an important variable. The robotic search and rescue systems will be acquired, maintained, and operated by local emergency response agencies that generally have limited and widely committed budgets. The design of the robots must therefore incorporate measures that reduce all reasons for cost to the local agencies. An additional factor to consider is the disposability of the robots. The conditions and tempo of many search and rescue missions may require that the robots be abandoned as soon as the mission objectives have been realized. "Throw-away" robots could enable search and rescue personnel to dedicate more time to search and rescue and less time to the support of their robotic tools. A varied inventory of small low-cost single-application robotic tools could permit the sacrifice of some of those tools in certain emergencies.

5.2.2 Reliability/Durability

In order for the robotic tools to provide the most useful assistance to the human search and rescue personnel, they need to add high reliability to their functionality under a broad range of mission conditions. As robots will be called upon under conditions that pose unacceptable risks to humans, the robots must be able to function by themselves[2] reliably under those very conditions. These conditions include toxic gas, absence of oxygen, water, high temperatures, and masses in motion (as are often associated with explosions, earthquakes, and collapsing buildings).

[2] Teleoperated robots meet in this context the requirement to function independently.

Waterproofing is needed to explore flooded basement areas and/or subterranean passages that connect buildings, as well as to operate under conventional firefighting conditions.

Temperature tolerance at least to 200 degree Fahrenheit for rescue missions as people cannot long survive in temperatures greater than 150 degrees. **[Mangolds]**

Waterproofing and invulnerability to high temperatures would also be necessary under the conditions prevailing at the WTC disaster site. **[Tillery]**

Remotely operated robots may continue to be used in firefighting and search and rescue even when humans are forced to withdraw from a building in imminent danger of collapse.

5.2.3 Range

The range of the robotic search and rescue deployments at the WTC site was generally less than 200 feet; however, other mission scenarios can be anticipated that would require much greater ranges. For example, the risks of toxic gas or of explosion could require large standoff distances for the human operators.

5.2.4 Speed

The tempo of operations at the WTC site did not demand rapid deployments of the robots. However, when the survival of injured and inaccessible persons is at stake, the speed of the response becomes critical. Similarly, if robots were deployed to fight fires and toxic contaminations directly, the speed of the responses could also be critical. In these latter cases the robots may be used to precisely deliver (or deploy) remedial agents.

5.2.5 Mobility

Search robots need to be smaller and more mobile. Of use would be the mobility capabilities and scale of spiders and hummingbirds. The hovering ability of hummingbirds could be quite useful in negotiating obstacles and chasms that could impede most ground mobile robots of any size. **[Tillery]**

Mobility[3] has two aspects: first is the ability to move over or around obstacles and the other is the ability to move between obstacles. The determining factors in these two situations are the relative sizes of the robot and of the obstacles. A large robot can move over small obstacles, while a small robot can often take advantage of the spaces that may exist between large obstacles to penetrate and pass between them. Unfortunately, the size and configuration of obstacles is quite unpredictable. A possible strategy may be to provide robots of a range of sizes and to deploy them in teams of mixed size to adjust to the conditions encountered. The Marsupial concept in which small robots are ported around by large robots may accomplish this strategy. The large robots negotiate obstacles within their operational scale, then, when obstructed by out-of-range obstacles, release the smaller robots to penetrate the obstacle gaps and continue with the mission.

[3] We have tended herein to use the terms *mobility* and *maneuverability* interchangeably. More precisely, *mobility* emphasizes movement across a dimension, while *maneuverability* emphasizes movement around or among non-traversables on a dimension.

5.2.6 Payload

The payload requirements for robotic tools will also be mission dependent, but will contribute significantly to the specification of the size requirements. The payloads of search robots may decrease with the miniaturization of sensors, radios, and other electronic equipment; however, the payloads of delivery and of recovery robots will be determined by the mass of the commodities that must be transported.

5.2.7 Weight

Weight, like cost, should be kept to a minimum. Low weight facilitates the transportation of the robot to its work site, and to some degree the navigation of the robot around its work site. It is only when masses oppose that weight provides any advantage.

Major contributors to weight in the current generation of robots are the electric motors and batteries. New power designs that include hydraulics and pneumatics may reduce the weight contributions of the motors, but the requirement to store on-board large quantities of electrical energy may remain a difficult problem to overcome. One possibility, however, is to engineer a power system that can extract energy from its environment. Solar powered robots are one example, but these are limited in application.

5.2.8 Sensors

The primary source of information used in teleoperation is vision, serviced by video camera. The video input is often difficult to interpret, however, when the images of few familiar objects are apparent in the frames. The rubble associated with disasters provides very few familiar or predictable sights. Orientation of the camera cannot be determined, nor can speed of the robot. Consequently, neither range nor depth information is easily extracted from the video alone.

A range finder is needed for navigation. **[Murphy]**

Audio is also an important source of information for human operators. Thus audio input from the robot should be available for the operator to sample as desired.[4]

5.2.9 Communications

Communications are critical to most robotic missions that we have considered. The communication methods and links are mission dependent. If the robot is tethered, then communications can be provided between the robot and the OCU, but would then be completely dependent upon the viability of the link. Should the link be broken, communications, the robot, and the mission would fail. A backup RF communications link could be an advantage for some urban search and rescue robot missions. The disadvantages of the use of a tether are in limited range, limited maneuverability, and limited survivability in traffic (none of which, however, may be major concerns in the urban search and rescue environment). The major disadvantage of RF communications is the line-of-sight requirement for the higher carrier frequencies (which remains a serious problem in urban environments). Thus, a combination of those two methods may be optimal.

[4] Many robots, including the URBOT and the Inuktun MicroTrac, provide audio to the operator. Some operators use this audio to assess the operational status of the robot.

5.2.10 Coordination

Essential to coordination is communications. We have outlined several examples where multiple robots may be coordinated to provide a greater number of services, under a greater variety of conditions, and at a faster pace than could be accomplished by a single robot or by a series of robots working sequentially without coordination. Some of the required coordination could be accomplished at the level of the operator control units, but other coordination should be most efficiently accomplished by the robots themselves. The robotics research and development community is actively exploring the protocols that could provide for this coordination among cooperating robots.

5.2.11 Trade-off Issues

The three general types of missions require different types of robot designs. The primary differences in design are related to the scales of the mission payloads and mission environments. Robot size obviously should be proportional to payload requirements. However, optimal robot size will likely be inversely related to obstacle size. That is, small robots are more likely to negotiate relatively large obstacles, while large robots are more likely to negotiate relatively small obstacles.

The problem with determining the appropriate robot size for the prevailing obstacle size is that most natural environments contain obstacles across a broad range of sizes. Manmade environments are much more predictable in terms of obstacle size, but disaster scenarios can considerably rearrange the lay and nature of the obstacles.

The primary function of maneuverability is to manage paths in which the sizes of the encountered obstacles are all optimal relative to the size of the mobile agent. The variety of navigable paths within any obstacle size range is limited, however. Thus, it may be better to employ small but highly mobile agents, and use mobility to increase the range of obstacle sizes that can be negotiated. The hummingbird concept is an example of increasing the mobility of a small agent, while the spider concept and the flipper design on the PACKBOT are examples of varying the size of the agent to increase its maneuverability.

The advantages of a tether were well demonstrated at the WTC site, yet the tether imposes a cost in terms of drag and other undesirable influences on the dynamics of the robot. The optimal mass of the tether can be calculated to provide the right combination of benefits for a particular size of robot. The benefits should include:

- Reliable wideband communications between the robot and the OCU
- Energy to the robot
- Vertical deployment and recovery capability for the robot and its payload
- Traceability to the robot should human intervention at the site of the robot be required

Other desirable options for the tether include:

- Detachability
- Spooling at either or both ends

6. REFERENCES

6.1 TEXT CITATIONS

[Mandelbrot] Mandelbrot, Benoit: "Fractals: Form, Chance, and Dimension," W. H. Freeman & Co., 1977.

[Timeline] WTC events as reported by the 18 September 2001 on-line version of the Los Angeles Times.

[Totals] http://www.firehouse.com/terrorist/

[USF] http://www.csee.usf.edu/robotics/crasar/

6.2 TEAM LEADS

[Everett] Bart Everett, Space and Naval Warfare Systems Center, San Diego, (619) 553-3672.

[Frost] Tom Frost, iRobot, (617) 629-0055 X280.

[Mangolds] Arnie Mangolds, Foster-Miller, (781) 684-4379.

[Murphy] Robin Murphy, Professor, University of South Florida, (813) 974-4756.

[Tillery] Chris Tillery, National Institute of Justice, (202) 305- 9829.

7. APPENDICES

7.1 ACRONYMS

COTS	Commercial Off-The-Shelf
CRASAR	Center for Robot Assisted Search and Rescue
DoD	Department of Defense
DoE	Department of Energy
DoJ	Department of Justice
FEMA	Federal Emergency Management Agency
FLIR	Forward-Looking Infra-Red
FOV	Field of View
GPS	Global Positioning System
INS	Inertial Navigation System
OCU	Operator Control Unit
RF	Radio Frequency
ROSAR	Remotely Operated Search and Rescue System
SSC San Diego	Space and Naval Warfare Systems Center, San Diego
USF	University of South Florida
WTC	World Trade Center

7.2 FIELD REPORTS AND RELATED NOTES

7.2.1 News Report on the One Successful Rescue

News report on the one occasion in which live people were discovered near the WTC disaster site.

http://www.7newskmgh.com/sh/news/stories/nat-news-95767220010912-100917.html

"New reports say that two firefighters -- not the previously reported five -- were rescued after being trapped in an SUV. In addition, the firefighters had been trapped since earlier today, not since Tuesday as previously reported.

The two firefighters were searching the rubble of the World Trade Center and became trapped in an air pocket Thursday before they were rescued hours later, said Fire Department Capt. Roger Sakowich.

He said only two were rescued. They got lost in an underground pocket beneath the rubble and were pulled out three to four hours later."

7.2.2 Mission Debrief, MPRS URBOT #2

Saturday night, 15 Sept 01 – (Bruch/Everett)
(Robot field-equipped with Indigo ALPHA FLIR (versus top drive camera))

Arrived IP approximately 2130; location south side of Carlisle St. between Washington St. and Greenwich St., two blocks south of WTC Tower 2.

Deployed URBOT #2 across Washington St., heading west, to south entrance of Marriott on north side of Carlisle. OCU equipped with high-gain directional Yagi, enabling good comms during entire transit, recorded as 250 feet line-of-sight by vehicle odometry. Compass headings appeared very repeatable, accurate to an estimated 10 degrees, and were very useful with regard to maintaining proper vehicle orientation and situation awareness when operating inside-out.

Climbed stairs into Marriott and entered service door, gained entry to lobby. Provided structural damage assessment of ceiling and surrounding area.

Relocated Operator and OCU to vicinity of building entrance to have more positive assessment capability of conditions external to hotel entrance. A number of workers observed the robot's entry and were milling about to see what transpired. URBOT entered elevator (door open), dropped approximately 12 inches due to observed but underestimated elevator offset. Unable to climb back out and exit elevator due to poor traction (significant powdered dust on floor). Threw track trying to exit elevator upon entangling large piece of debris, visually identified as elevator ceiling trap door, which was laying on floor of elevator car. Turned off headlights to conserve battery power.

Manually recovered robot, exited building.

Headed east to intersection of Carlisle and Washington, turned north up Washington, re-entered Marriott mid-block between Carlisle and Albany (near flower shop). Found good comms could be maintained non-line-of-sight by bouncing RF signal off face of building on opposite side of street. Uncooled Indigo Alpha FLIR generally of VERY limited utility for visual navigation in this environment, though in all fairness we were not able to implement the RS-232 camera-control interface and associated software during the emergency field upgrade. Probably would have been useful earlier in smoke-obscured conditions when searching for survivors, but no warm bodies likely this late in scenario.

Gained access to second floor via stairs. Heavy debris, no major structural damage. Encountered fire hose snaked back and forth across floor, URBOT was able to successfully negotiate with no observed problems. Successfully navigated past and then under scaffolding, which was apparently being used in support of ceiling maintenance at time of incident. Returned down stairwell and inspected large assortment of wine bottles (unbroken) in wine rack in vicinity of restaurant area. Chairs and tables basically intact and largely undisturbed except for very heavy dust layer. Zoomed in on multiple objects of interest, but basically there was very little damage within this building, despite it's close proximity to the pile.

Exited east entrance back onto Washington St., headed north, turned west on Albany, re-entered north entrance of Marriott. Limited ability to penetrate very deep into structure from this entrance, nothing very significant noted, retraced path and exited building onto Albany St., headed east to Washington, south to parking garage structure near IP.

Entered parking structure, attempted but unable to climb stairs at southwest corner due to stair blockage near IP. URBOT flipped over on its back in process, but automatically recovered, succesfully switching cameras and inverting drive controls. Unfortunately ran out of video tape and so this last evolution not recorded. Returned to IP and secured URBOT #2 and OCU. Run time in excess of 2 hours, OCU video time-stamped, plenty of battery power remaining.

End of mission.

7.3 IMAGES OF ROBOTICS ACTIVITY AT THE WTC

Man Portable Robotic System (MPRS) Urban Robot (URBOT) Operator Control Unit (OCU)
Bart Everett (Code 23701), Michael Bruch (Code 2371)
WTC at Washington St. and Carlisle St. (looking north)

Foster Miller, Inc. (FMI) Talon Operator Control Unit (OCU)
Robin Laird (Code 2371)
WTC at Albany St. near Washington St. (looking east)

Robotic Assets of “National” Center for Robot-Assisted Search and Rescue (CRASAR) Unit
SSC San Diego URBOT, FMI Talon, iRobot PackBot, Inukten Microtraks
FEMA HQ Jacob Javits Convention Center (NYC)

FMI Talon Crossing Street to Marriott
NYC Contractor Cleanup Work Crew
WTC corner of Washington St. and Carlisle St. (looking north)

WTC Tower 2 Ground Zero
NYC Contractor Cleanup Crew
Near corner of Liberty St. and Washington St. (looking north)

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